

Feb. 4, 1964

H. SEIDEL
GYROMAGNETIC MODE TRAVELLING-WAVE PARAMETRIC
AMPLIFIER AND OSCILLATOR

3,120,646

Filed Oct. 25, 1961

4 Sheets-Sheet 1

FIG. 2

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4 Sheets-Sheet 2

FIG. 3

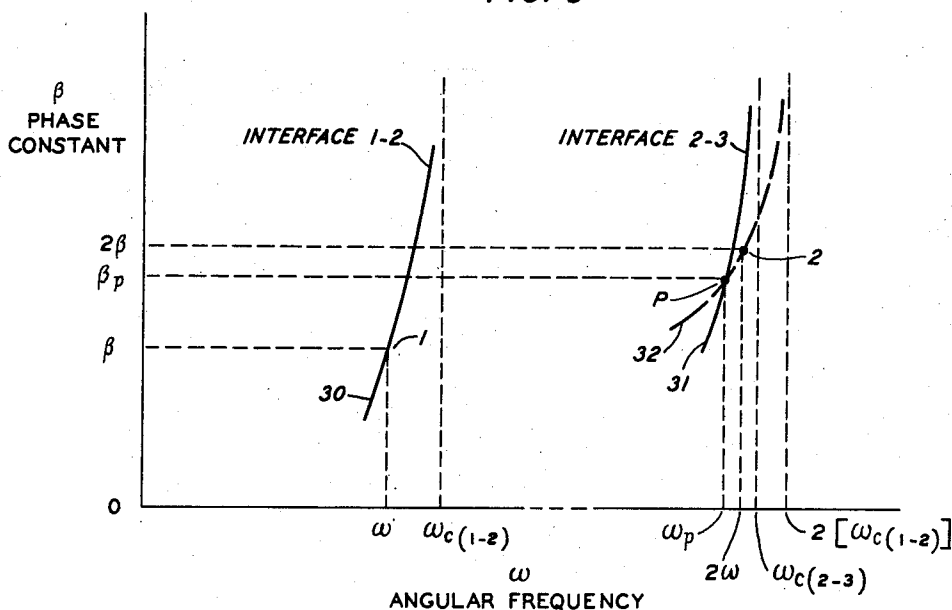
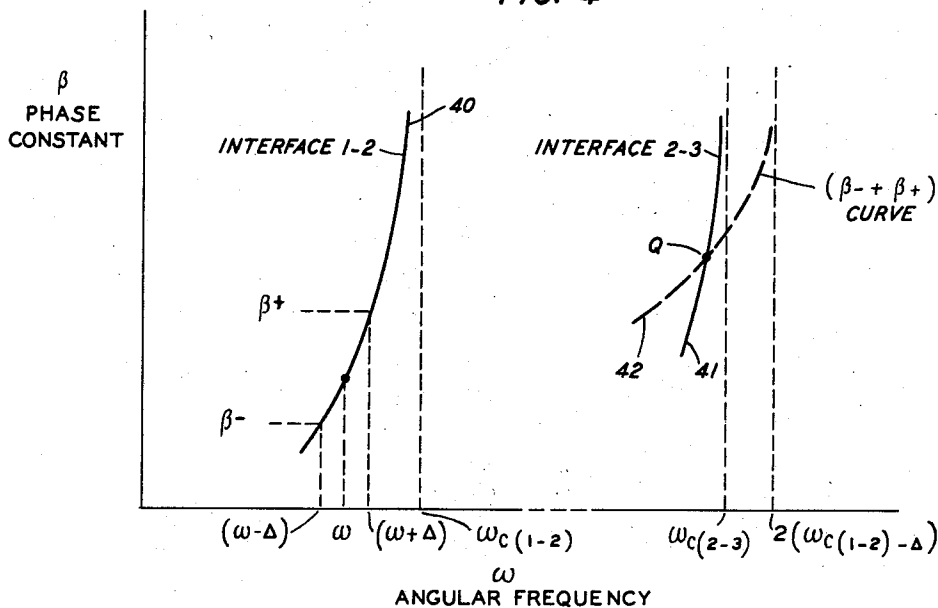


FIG. 4



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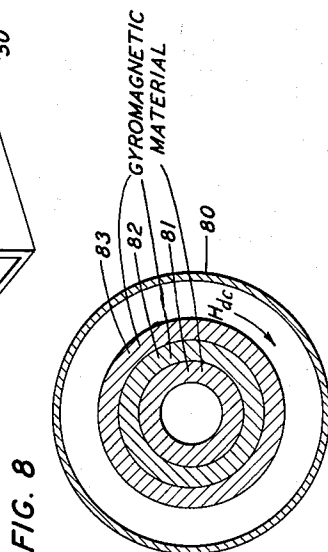
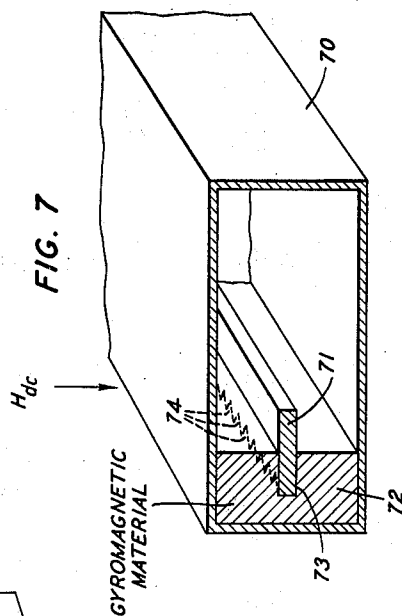
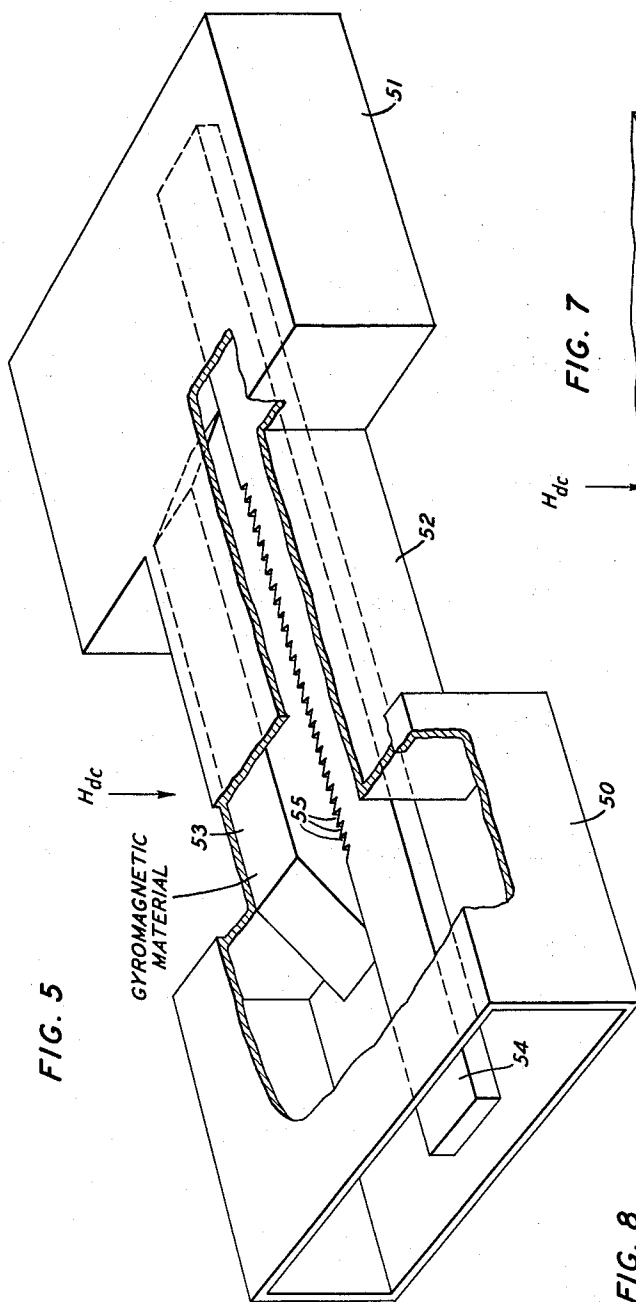
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4 Sheets-Sheet 3



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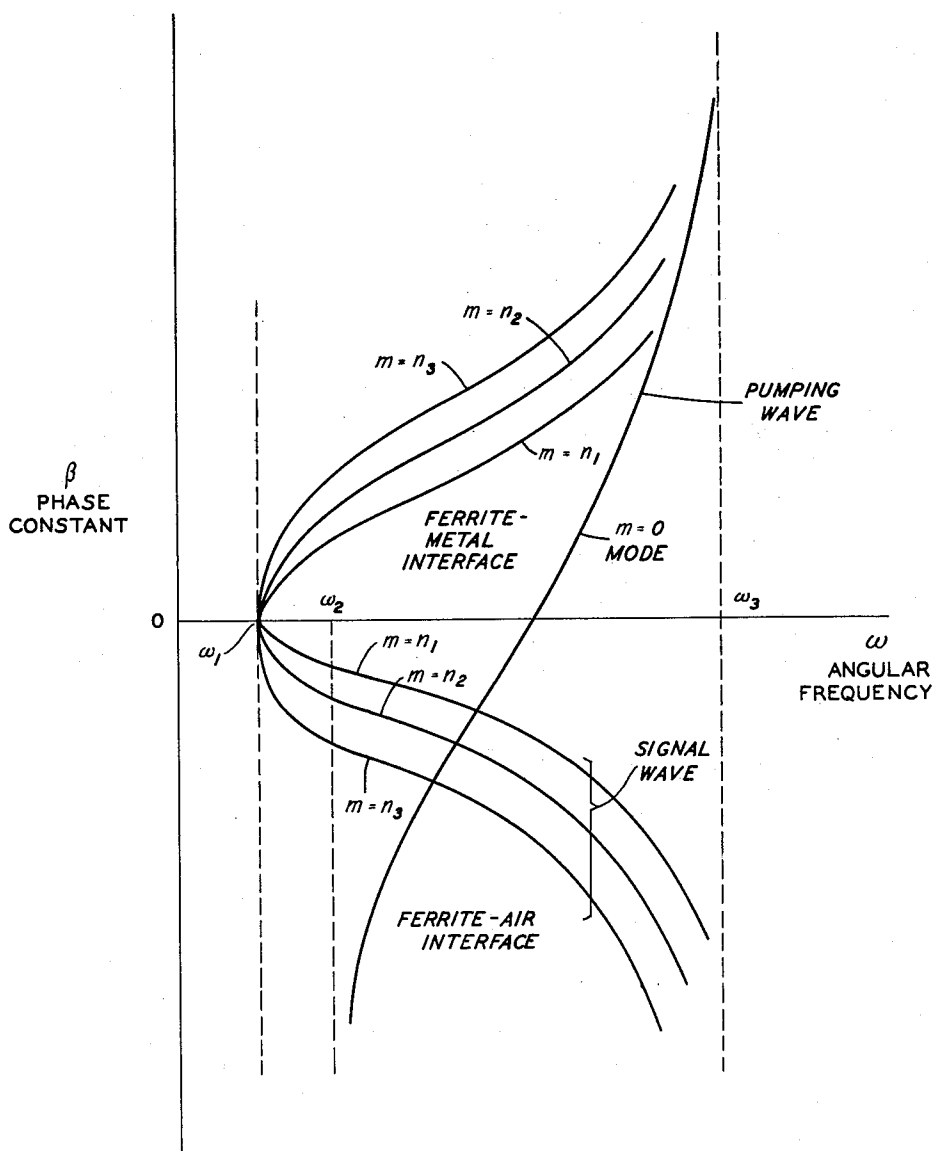
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4 Sheets-Sheet 4

FIG. 6



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1

3,120,646
**GYROMAGNETIC MODE TRAVELLING-WAVE
PARAMETRIC AMPLIFIER AND OSCILLATOR**
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Laboratories, Incorporated, New York, N.Y., a corpo-
ration of New York
Filed Oct. 25, 1961, Ser. No. 147,641
11 Claims. (Cl. 330-4.6)

This invention relates to the amplification and genera-
tion of high frequency electromagnetic wave energy and
more particularly to traveling wave, solid state parametric
amplifiers and oscillators.

In applicant's paper entitled "Character of Waveguide
Modes in Gyromagnetic Media" published in the Bell Sys-
tem Technical Journal, volume 36, March 1957, pages
409 to 426 and in a paper by applicant and R. C. Fletcher
entitled "Gyromagnetic Modes in Waveguide Partially
Loaded with Ferrite" published in the Bell System Tech-
nical Journal, volume 38, November 1959, pages 1427 to
1456, the transmission of wave energy in isotropic and in
anisotropic waveguides is considered. In particular, it is
shown that there are an infinite number of modes capable
of propagating in a waveguide loaded with gyromagnetic
material no matter how small the guide. Since these
modes have no analog in waveguides filled with isotropic
material, these modes have been characterized as "gyro-
magnetic modes."

It is a characteristic of gyromagnetic modes that the
wave energy associated therewith tends to concentrate
about a boundary or interface of the gyromagnetic ma-
terial. It is also a characteristic of gyromagnetic modes
that the distribution of wave energy is virtually indepen-
dent of the nature of the waveguiding structure. This is
in contrast to the normal waveguide modes which propa-
gate in gyromagnetic-loaded waveguides. Although the
field pattern for these normal modes is distorted by vir-
tue of the presence of the gyromagnetic material, the field
pattern is nevertheless influenced to a considerable ex-
tent by the presence of the waveguiding structure. By
contrast, the distribution of wave energy for the gyro-
magnetic modes is a function of the nature of the gyro-
magnetic interface to which the wave is bound. Thus,
for example, at a gyromagnetic-air boundary, the field dis-
tribution is a maximum at the plane of the interface and
drops off exponentially as a function of the distance from
the interface.

In applicant's copending applications Serial No. 60,429,
filed October 4, 1960, now U.S. Patent 3,010,084, issued
November 21, 1961 and Serial No. 774,547, filed Novem-
ber 17, 1958, now U.S. Patent 3,010,086, issued Novem-
ber 21, 1961, there are disclosed a new class of isolators
whose operation is based upon the generation and propa-
gation of these gyromagnetic modes. It is now proposed,
however, to utilize these modes in connection with para-
metric amplifiers and oscillators of reduced size, simple
construction and greater inherent stability.

Accordingly, it is the broad object of this invention to
obtain parametric amplification of high frequency wave
energy propagating in one of the gyromagnetic modes.

As is well known, the magnetization of a gyromagnetic
material precesses under the influence of a pumping mag-
netic field at a frequency f_p and a steady polarizing mag-
netic field. If now there is superimposed upon such a
system the magnetic field of a signal wave at a frequency
 f_s , the steady field is modulated so that the precessional
frequency of the magnetization is varied. In the presence
of the gyromagnetic material the signal wave mixes with
the pumping wave to produce a component of magnetic
field at the so-called "idler" frequency f_i such that

$$f_p = f_s + f_i$$

2

In a paper by P. K. Tien and H. Suhl entitled "A Travel-
ing-Wave Ferromagnetic Amplifier," published in the
April 1958 Proceedings of the Institute of Radio Engi-
neers, pp. 700 to 706, it is further pointed out that in a
traveling wave system an additional, preferred condition
for parametric amplification is that the phase constant of
the pumping wave β_p and the phase constants of the signal
 β_s and the idler β_i be related such that

$$\beta_p = \beta_s + \beta_i$$

It is, accordingly, a more specific object of this inven-
tion to obtain parametric amplification of signal wave
energy by suitably relating the frequency and phase con-
stants of propagating gyromagnetic mode waves.

In accordance with the invention, guided wave energy
propagating in an isotropic wave path in one of the normal
propagating TE, TM or TEM modes is coupled from said
normal mode to one of the gyromagnetic modes of wave
propagation. Specifically, gyromagnetic propagating
modes are induced in a gyromagnetic element at a signal
frequency and at a pumping frequency higher than said
signal frequency. By suitably selecting the gyromagnetic
modes induced and the electrical properties of the gyro-
magnetic material, the preferred frequency and phase
relationships are established for parametric amplification.

In a first embodiment of the invention a composite ele-
ment consisting of three slabs of gyromagnetic material is
disposed in a waveguiding structure whose internal di-
mensions are such that the loaded guide is cut-off for the
normal waveguide modes over the frequency range of in-
terest. This insures that the only propagating modes are
the gyromagnetic modes. The three slabs are in the form
of flat plates arranged with their broad surfaces contiguous
and parallel to each other and to the direction of the ap-
plied steady biasing field. The plates are energized in a
manner to induce the same order gyromagnetic mode at
the pumping frequency and at the signal frequency.

In a second embodiment of the invention two distinctly
different gyromagnetic modes are induced in a single
gyromagnetic element. One of the modes is derived from
a TE mode wave whereas the other mode is derived from
a TEM mode wave. Scattering techniques are used to
couple energy from the TEM mode to one of the gyro-
magnetic modes.

It is an advantage of an amplifier constructed in ac-
cordance with the invention that it has greater inherent
stability and, consequently, does not require separate
means for suppressing amplification in the reverse direc-
tion. This stability comes about by virtue of the fact
that the gyromagnetic modes are nonreciprocal and, hence,
the conditions favorable for amplification in one direction
of propagation are not satisfied for propagation in the re-
verse direction. A second advantage of an amplifier con-
structed in accordance with the invention resides in the
fact that amplification is produced uniformly and con-
tinuously along the gyromagnetic material rather than at
discrete intervals. Furthermore, the gyromagnetic modes
propagate with a propagation velocity several orders of
magnitude smaller than the normal waveguide modes.
As such they constitute a slow-wave structure of exceed-
ingly simple design which affords a high level of interac-
tion between the pumping wave and the signal wave there-
by resulting in a substantial amount of gain per unit
length of amplifier.

These and other objects and advantages, the nature of
the present invention, and its various features, will ap-
pear more fully upon consideration of the various illus-
trative embodiments now to be described in detail in
connection with the accompanying drawings, in which:

FIG. 1 is a first embodiment of the invention using a
composite gyromagnetic element;

FIG. 2, given by way of explanation, illustrates the

field distribution about the interfaces of the composite gyromagnetic element used in the embodiment of the invention shown in FIG. 1;

FIGS. 3 and 4 show, by way of illustration, the manner in which the phase constant of the gyromagnetic mode varies as a function of the angular frequency and further illustrates the manner in which an amplifier in accordance with the invention can be graphically designed;

FIG. 5 is a second embodiment of the invention using a combination of TE and TEM mode waves to induce two different gyromagnetic mode waves of different order;

FIG. 6 given by way of explanation, illustrates the manner in which the phase constant of the gyromagnetic modes induced in the embodiment of FIG. 5 vary as a function of the angular frequency;

FIG. 7 shows a modification of the embodiment of FIG. 5; and

FIG. 8 shows the cross section of an amplifier, in accordance with the invention, adapted for use with the circular electric mode of wave propagation.

Referring to FIG. 1, there is shown a first embodiment of a parametric amplifier in accordance with the principles of the invention comprising first and second longitudinally spaced sections 10 and 11 of bounded electrical transmission line for guiding electromagnetic wave energy. The sections are coaxially aligned along a common longitudinal axis $x-x$ and can be of the metallic shield type having a rectangular cross-section whose wide dimension is at least one-half wavelength of the wave energy to be propagated therethrough, and whose narrow dimension is typically one-half of the wide dimension. So proportioned, waveguides 10 and 11 are supportive of one of the normal TE or TM waveguide modes including, at least, the dominant mode, known in the art as the TE_{10} mode, in which the electric lines of force extend from the bottom to the top of the waveguide, perpendicular to the wide guide walls and in which the intensity of the electric field varies sinusoidally along the wide dimension, reaching a maximum at the center of the guide and being substantially zero at the edges.

Located between guides 10 and 11 is a third section of reduced width waveguide 12 whose effective transverse cross-sectional dimensions (when loaded with gyromagnetic material) are to be less than one-half of the free-space wavelength of the wave energy to be propagated therethrough. Thus, though characterized as a waveguide, section 12 is, in fact, proportioned to be cut-off for the normal waveguide modes since, to the extent that such modes do exist in guide 12, they represent a loss.

In the embodiment of FIG. 1, waveguide 12 is illustrated as having a rectangular cross-section. The cross-sectional geometry of guide 12 can, however, be oval or circular without in any way affecting the operation of the device. Advantageously, however, the transverse dimensions are less than one-half the free-space wavelength of the energy to be propagated therethrough, as indicated hereinbefore.

Located within section 12 is a composite element 13 of active material comprising the three slab-like elements 1, 2 and 3 each of a different gyromagnetic material. The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetic polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a significant precessional motion at a frequency within the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion is characterized as having an angular momentum and a magnetic moment. Typical of such materials are ionized gases, paramagnetic materials and ferromagnetic materials, the latter in-

cluding the spinels such as magnesium aluminum ferrite, aluminum zinc ferrite and the garnet-like materials such as yttrium iron garnet. In the embodiment shown in FIG. 1, element 13 is made of ferrite materials. Accordingly, in the discussion to follow the terms "ferrite," "ferrite-air," "ferrite-metal," et cetera, will be used to describe various aspects of the invention. However, it is to be understood that other gyromagnetic materials can be used equally as well and that the use of ferrite is merely intended to be illustrative.

The elements 1, 2 and 3 are aligned with their broad surfaces parallel to each other and to the narrow walls of guides 10 and 11. The adjacent broad surfaces of elements 1 and 2 are placed in contact defining a first interface 1-2, and the adjacent broad surfaces of elements 2 and 3 are placed in contact defining a second interface 2-3.

Composite element 13 is preferably symmetrically located within guide 12 although its precise location therein is not critical. Element 13 can either completely fill guide 12 or it can be spaced from any of the various guide walls. In the embodiment of FIG. 1, element 13 is shown in contact with the top and bottom walls but spaced away from the side walls of guide 12. To facilitate coupling between the waveguide mode and the gyromagnetic mode, the composite element 13 advantageously extends into guides 10 and 11 and is preferably tapered at both ends.

A static magnetic polarizing field H_{dc} is applied in a direction parallel to the broad surfaces of elements 1, 2 and 3. The polarizing field can be supplied by any suitable means (not shown) such as an electric solenoid, a permanent magnetic structure or, in some instances, the elements 1, 2 and 3 can be permanently magnetized.

In operation, wave energy at a pumping frequency f_p , indicated by an arrow 14, is applied to waveguide 10 from a source of wave energy (not shown). Simultaneously, signal wave energy at a frequency f_s , indicated by an arrow 15, is applied to waveguide 10 from a second source of wave energy (not shown). Wave energy at both these frequencies propagates along guide 10 in one of the normal TE waveguide modes. Upon reaching guide 12, however, these normal TE waveguide modes cannot propagate due to the fact that the ferrite-loaded guide 12 is cut-off at both frequencies f_p and f_s . However, as was pointed out in the above-cited paper by H. Seidel and R. C. Fletcher, there are an infinite number of modes capable of propagating in a waveguide partially filled with gyromagnetic material no matter how small the guide. These modes are called "gyromagnetic modes" since they have no analog in waveguides filled with isotropic material.

Typically, the gyromagnetic modes propagate as boundary waves in which the energy concentrates at one of the interfaces of the gyromagnetic material, falling off exponentially as a function of distance from the interface. The various gyromagnetic modes differ from each other in the spatial distribution of the magnetization vectors within the gyromagnetic material and are related to the inducing mode and the manner of coupling between the inducing mode and the gyromagnetic mode. In the embodiment of FIG. 1 the primary mode induced in the gyromagnetic material is the lowest order, $m=0$, gyromagnetic mode.

FIG. 2 is a cross-sectional view showing the three gyromagnetic elements 1, 2 and 3 and guide 12. It will be noted that there are four interfaces. The first is the ferrite-air interface associated with element 1; the second is the ferrite-ferrite interface 1-2; the third is the ferrite-ferrite interface 2-3; and the fourth is the ferrite-air interface associated with element 3. Each of these is capable of supporting gyromagnetic modes.

In accordance with the invention, however, the electrical and physical properties of composite element 13 are selected so that the frequencies of interest, the wave en-

5

ergy is concentrated at the 1-2 and 2-3 ferrite-ferrite interfaces. In particular, if the pumping wave energy is concentrated at one interface and the signal wave energy at the other and if, in addition, element 2 is thin, there is a substantial region of overlap for the two waves and a resulting strong region of interaction of the waves and the gyromagnetic material. This is illustrated in FIG. 2 in which the two curves 20 and 21 show the distribution of wave energy at interfaces 1-2 and 2-3 for the pumping frequency f_p and the signal frequency f_s . By making the transverse dimension t of element 2 small, there is considerable interaction between the waves and element 2. Furthermore, since the velocity of propagation of the gyromagnetic modes is one or more orders of magnitude less than that of the normal waveguide mode, this interaction persists for a relatively long time per unit length of gyromagnetic material.

In the above-mentioned publication by P. K. Tien and H. Suhl, the optimum conditions for parametric amplification in a traveling wave configuration are given as

$$f_p = f_s + f_i \quad (1)$$

$$\beta_p = \beta_s + \beta_i \quad (2)$$

where f_p , β_p , f_s , β_s and f_i , β_i , are the frequencies and phase constants of the pumping wave, signal wave and the idler wave, respectively. By virtue of the interactions of the pumping wave and the signal wave in the gyromagnetic material, it is apparent that the first condition is automatically satisfied. Condition 2, though not essential, defines the condition of maximum gain. Tien and Suhl show that to the extent that Equation 2 is not satisfied, the gain is reduced. Accordingly, condition 2 is the preferred condition.

Accordingly, the preferred design of a parametric amplifier in accordance with the invention involves a selection of suitable gyromagnetic material whose electrical properties are such as to make it possible to satisfy the frequency and phase constant requirements set forth in Equations 1 and 2. An amplifier in accordance with the invention can be readily designed graphically from a plot of the frequency-phase constant curve for each ferrite-to-ferrite interface. Typically, the phase constant increases as a function of frequency and approaches infinity at a critical frequency ω_c . This occurs at the 1-2 interface for the $m=0$ gyromagnetic mode at

$$\omega_{c(1-2)} = \frac{\sigma -}{2} \pm \left[\frac{\sigma -^2}{4} + \gamma H_{dc} (\gamma H_{dc} + \sigma +) \right]^{1/2} \quad (3)$$

for which

$$\sigma + = \frac{\gamma}{2} (4\pi M_2 + 4\pi M_1) \quad (4)$$

and

$$\sigma - = \frac{\gamma}{2} (4\pi M_2 - 4\pi M_1) \quad (5)$$

where:

$4\pi M_1$ and $4\pi M_2$ are the saturation magnetizations for gyromagnetic slabs 1 and 2, respectively,

γ is the ratio of magnetic moment to angular momentum for an electron, generally equal to 2.8 mc. per oersted, and

H_{dc} is the steady biasing field.

Knowing the frequency of the signal to be amplified, $4\pi M_1$, $4\pi M_2$ and H_{dc} are selected such that $\omega_{c(1-2)}$, the critical frequency for interface 1-2, is somewhat higher than the signal frequency.

Using the same values already given for H_{dc} and $4\pi M_2$, a similar calculation is made for the 2-3 interface. Since the pumping frequency is equal to twice the average of the signal frequency and the idler frequency, $4\pi M_3$ is selected such that $\omega_{c(2-3)}$ is slightly less than twice $\omega_{c(1-2)}$.

6

The saturation magnetization of ferrite materials can be varied in many ways as, for instance, by varying the ratio of magnetic to nonmagnetic materials in either the divalent or trivalent sites or by varying the density of the ferrite material. For a discussion of ferrites and, in particular, the saturation magnetization of ferrite see "Ferrites" by J. Smit and H. P. J. Wijn, pages 147 to 160 published in 1959 by J. Wiley & Sons.

FIG. 3 is a graph whose abscissa is angular frequency ω , and whose ordinate is phase constant β . The two critical frequencies $\omega_{c(1-2)}$ and $\omega_{c(2-3)}$ have been plotted and a portion of the $\beta-\omega$ curves for the two interfaces have also been plotted. The latter are computed for large values of β since the region of large phase constants define a preferred range of operation in that they imply a slower traveling wave and hence a longer interaction time for the pumping and signal waves in the gyromagnetic material.

To arrive at an operating point, the (1-2) interface curve 30 is replotted by doubling the frequency and phase constant values at points along curve 30 to obtain a second 1-2 interface curve 32 shown dotted. For example, a point 1 on curve 30 having an angular frequency ω and a phase constant β is plotted as point 2 on curve 32 at a frequency 2ω and a phase constant 2β . Curve 32 intersects the 2-3 interface curve 31 at a point P. Where curve 32 intersects curve 31 defines a point on curve 31 (ω_p , β_p) and a point on curve 30 ($\omega_{p/2}$, $\beta_{p/2}$). This point satisfies the conditions for parametric amplification in the degenerate mode. That is

$$2\omega_s = \omega_p$$

and

$$2\beta_s = \beta_p$$

For operation in the nondegenerate mode, we proceed as before by identifying two critical frequencies and plotting a portion of each interface curve as shown in FIG. 4. However, curve 42 which is derived from curve 40 is obtained in a slightly different manner than curve 32 in FIG. 3. Curve 42 is obtained by selecting two frequencies $\omega - \Delta$ and $\omega + \Delta$ which represent the idler and signal frequencies where 2Δ is the desired separation between said frequencies. For $\omega - \Delta$ there is a corresponding phase constant β^- and for $\omega + \Delta$ there is a corresponding phase constant β^+ . Curve 42 is a plot of $(\beta^- + \beta^+)$ as a function of $[(\omega - \Delta) + (\omega + \Delta)]$. The intersection Q of curve 42 with the 2-3 interface curve defines the operating point for parametric amplification in the nondegenerate mode. That is, it defines a point for which the sum of the signal and idler frequencies equals the pumping frequency and for which the sum of the phase constant of the signal and idler equals the phase constant of the pumping wave.

For an amplifier to be operated at a signal frequency of about 500 megacycles per second, saturation magnetizations of 357, 760 and 1430 gauss for elements 1, 2 and 3 would be typical. The critical frequency at the two interfaces would be 563 megacycles per second and 938 megacycles per second.

Another consideration in the design of an amplifier in accordance with the embodiment of the invention shown in FIG. 1 is the thickness t of the center slab 2. Preferably the slab is very thin so that there is a maximum overlapping of the field distribution at the two interfaces. However, if the slab is too thin the interfaces are no longer clearly defined electrically and the boundary waves are not properly established. Accordingly, a compromising thickness is recommended for which the field has decreased to approximately one-third to one-tenth of its maximum intensity. Since the field decreases exponentially as a function of distance from the interface and is related to the phase constant β of the

interface mode, the preferred thickness is defined such that

$$\epsilon^{-|\beta|t} \approx 0.1 \text{ to } 0.3$$

or

$$t \approx \frac{2.3}{|\beta|} \text{ to } \frac{3.4}{|\beta|}$$

where β is the phase constant for the lowest frequency wave (i.e., the idler or signal frequency).

In the embodiment of FIG. 1 described above, both the signal and the pumping wave propagated in waveguides 10 and 11 in one of the normal TE waveguide modes and the lowest order, $m=0$, gyromagnetic mode was induced in the gyromagnetic material. However, other types of incident modes and higher order gyromagnetic modes can be used for either the signal or the pumping wave or for both. This permits a modification in structure and an alternate embodiment of the invention as shown in FIG. 5.

This second embodiment of the invention comprises a pair of longitudinally spaced rectangular waveguides 50 and 51 proportioned to support the pumping wave in a TE waveguide mode. Interposed between guides 50 and 51 is a third waveguide 52 of reduced width within which there is located an element 53 of magnetically biased gyromagnetic material. In the illustrative embodiment of FIG. 5, element 53 is in the form of a thin slab of ferrite material which extends longitudinally within guide 52 and is transversely displaced with respect to the guide axis so that one of the broad surfaces of element 53 is in contact with one of the vertical walls of guide 52 defining a ferrite-metal interface. The opposite broad surface of element 53 is exposed to whatever dielectric material fills guide 52. In the embodiment of FIG. 5 the dielectric filling is assumed to be air. Accordingly, this opposite surface defines a ferrite-air interface.

Ferrite element 53 preferably extends into guides 50 and 51 a slight distance and is tapered in a manner to minimize reflections and to couple between the waveguide mode and the gyromagnetic mode. It will be noted, that in contrast to the composite gyromagnetic element 13 used in the embodiment of FIG. 1, element 53 is composed of only one type of gyromagnetic material.

The signal wave in the embodiment of FIG. 5 is propagated in the TEM mode by means of a two conductor transmission line which comprises as the outer conductor the waveguides 50, 51 and 52 and an inner conductor 54 which is shown as a thin rectangular conductive member extending longitudinally through the three guides 50, 51 and 52.

Because coaxial transmission lines do not cut-off in the same sense as do waveguides and because the propagation properties of the gyromagnetic modes are substantially different than the TEM mode, there is little tendency for the signal wave to couple from the TEM mode to any of the gyromagnetic modes. Accordingly, special means are provided to effect such coupling. In my copending application Serial No. 774,547, referred to above, now United States Patent 3,010,086 issued November 21, 1961, a number of scattering techniques are shown to accomplish this coupling. One of the methods used and described in some detail in said copending application, comprises placing a number of discontinuities along the wave path in the form of indentations 55 along the inner conductor 54 immediately adjacent to the gyromagnetic material 53. The discontinuities effectively interrupt the longitudinal symmetry of the wave path creating higher order space harmonics. In the presence of the gyromagnetic material, wave energy is coupled between the modified TEM mode wave and one or more of the higher order gyromagnetic mode waves.

Because the two gyromagnetic modes induced in the gyromagnetic material in the embodiment of FIG. 5 are derived from two distinctly different types of incident modes (the TE mode and TEM mode) and different cou-

pling means, the gyromagnetic modes themselves are also different. As such, each of the gyromagnetic modes can be separately selected to satisfy the preferred frequency and phase velocity conditions as set forth above in Equations 1 and 2 and for this reason only one type of gyromagnetic material is needed.

In FIG. 2 of the publication by applicant and R. C. Fletcher cited above, a plot of the variation of the phase constant as a function of the steady biasing magnetic field is shown for various propagating gyromagnetic modes. In FIG. 6 a slightly modified version of this plot is given showing the variation of phase constant as a function of angular frequency for the $m=0$ mode and for three arbitrarily selected higher order modes $m=n_1$, $m=n_2$ and $m=n_3$.

The $m=0$ mode wave propagates between frequency ω_2 and ω_3 where

$$\omega_2 = \gamma(H_{dc} + 2\pi M)$$

and

$$\omega_3 = \gamma(H_{dc} + 4\pi M)$$

It will be noted that in this interval the $m=0$ mode is capable of propagating as either a backward wave (negative β) at the ferrite-air interface or as a forward wave (positive β) at the ferrite-metal interface.

The $m=n$ mode waves propagate between frequencies ω_1 and ω_3 where

$$\omega_1 = \gamma\sqrt{H_{dc}(H_{dc} + 4\pi M)}$$

and

$$\omega_3 = \gamma(H_{dc} + 4\pi M)$$

In this interval, the $m=n$ modes also propagate either as a backward wave (negative β) at the ferrite-air interface or as a forward wave (positive β) at the ferrite-metal interface.

To ascertain an optimum operating point, a graphical construction of the type outlined above is made. Because of the plurality of higher order modes and the two modes of propagation that are possible for all the modes, various combinations of positive and negative propagating waves are possible. One combination of modes includes a ferrite-metal mode for the signal and a ferrite-metal mode for the pumping wave.

Because the propagation constant at any frequency increases with the mode order, operation with a higher order mode is to be preferred. The distribution of modes induced is a function of the discontinuities 55 along conductive member 54. In general, the larger the number of discontinuities per unit length and the more abrupt the discontinuities, the higher the mode order of the induced gyromagnetic mode.

Some improvement in the conversion efficiency from the TEM mode to the ferrite-metal gyromagnetic mode can be effected by reducing the distance between the discontinuities and the ferrite-metal interface. This can be accomplished by cutting a longitudinal slot along the ferrite and inserting the conductive member in the slot thus cut. This is illustrated in FIG. 7 which shows a portion of reduced width waveguide 70, ferrite element 72 including a slot 73 and the inner conductor 71 located within said slot 73. This has the effect of placing the indentations 74 closer to the ferrite-metal interface.

Additional improvements can be realized in the several embodiments of the invention described above by reducing the height of the gyromagnetic material. This has the effect of increasing the phase constant of the gyromagnetic modes (reducing the velocity of propagation) thereby increasing the effective interaction time and thus increasing the gain per unit length of gyromagnetic material.

Many of the currently popular solid-state traveling-wave amplifiers, such as the three level maser described by R. W. De Grasse, J. J. Kostelnick and H. E. D. Scovil in an article entitled "The Dual Channel 2390-mc Traveling-Wave Maser," published in the July 1961 Bell System Technical Journal, pages 1117 to 1127, are reciprocal in

their action and, consequently, separate and distinct means must be provided in order to suppress amplification in the reverse direction and thus insure stable operation of the amplifier. Such special precautions are unnecessary, however, for amplifiers constructed and operated in accordance with the teachings of the instant invention since they are inherently stable in that their action is nonreciprocal. For wave energy propagating in the reverse direction, the situation is radically altered and favorable conditions for parametric amplification are not satisfied. To the contrary, incident wave energy in the reverse direction is either dissipated by absorption within the gyromagnetic material or propagates through without interacting in the manner to produce appreciable amplification. Hence, amplifiers of the type described herein are inherently much more stable than the bilateral amplifiers of the type described by De Grasse et al.

In the various embodiments described, one or more of the incident modes were characterized as TE mode wave propagating in a rectangular waveguide. This was in no way intended to limit the invention to any particular mode wave. To the contrary, other modes, such as TE modes in circular waveguides and TM modes in rectangular and circular waveguides can be used. For example, FIG. 8 shows a cross-section of an embodiment of the invention similar to the embodiment shown in FIG. 1 adapted to operate in conjunction with the circular electric mode of wave energy and comprises a circular waveguide 80 and three concentric ferrite cylinders 81, 82 and 83 circumferentially biased by means of steady magnetic biasing field H_{dc} induced in any convenient manner well known in the art. Adjacent surfaces of the ferrite cylinders are in contact to form a pair of ferrite-ferrite interfaces. The ferrite-loaded guide which is cut-off for the circular electric mode at the signal and pumping frequencies is typically placed between sections of circular waveguide supportive of the circular electric mode at the frequencies of interest and in all respects operates in the manner described above in connection with the embodiment shown in FIG. 1.

The technique of cutting off the waveguide is a convenient, although not necessary, means of coupling between the incident mode and the gyromagnetic mode. Other techniques (such as, for example, the scattering technique used in connection with the embodiment of FIG. 5) can alternatively be used to couple between an incident mode and a gyromagnetic mode. The efficiency of the amplifier, however, varies as a function of the efficiency of the mode conversion technique employed. It is, of course, preferred that all of the incident wave energy be converted into the desired gyromagnetic mode. To the extent that this is not accomplished, the unconverted or improperly converted wave energy is either not amplified or, in some instances, is attenuated and represents instead a loss to the system.

While the various embodiments described above have been characterized as amplifiers, it is known that by increasing the amplitude of the pumping wave about a critical threshold level for the system, a parametric amplifier can be made to oscillate. This is pointed out by H. Suhl in his article "Proposal for a Ferromagnetic Amplifier in the Microwave Region," published in *The Physical Review*, vol. 106, April 15, 1957. Thus, any of the illustrative embodiments of the invention described herein can be used as an oscillator, the only difference being that no signal wave is applied to the device.

It is, accordingly, understood that the above-described arrangements are illustrative of but a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A parametric amplifier comprising a slab of magnetically polarized gyromagnetic material having a pair of spaced planar interfaces;

means for inducing a first gyromagnetic propagating mode having a phase constant β_1 at one of said interfaces at a frequency f_1 ;

means for inducing a second gyromagnetic propagating mode having a phase constant $2\beta_1$ at the other of said interfaces at a frequency $2f_1$;

said interfaces being spaced a distance t given approximately by

$$\frac{2.3}{|\beta_1|} < t < \frac{3.4}{|\beta_1|}$$

and means for extracting amplifier wave energy from said amplifier at said frequency f_1 .

2. A parametric amplifier comprising first and second waveguiding paths capable of supporting energy in one of the normal modes of wave propagation at a signal frequency f_s and at a pumping frequency of f_p higher than said signal frequency;

a third waveguiding path proportioned to be cut-off for said normal waveguide modes disposed between and electromagnetically coupled to said first and second waveguiding paths;

said third waveguiding path including three slabs of dissimilar gyromagnetic materials defining a pair of spaced planar interfaces;

means for magnetically biasing said slabs; one of said interfaces being capable of propagating said pumping frequency wave in a gyromagnetic mode of wave propagation with a phase constant β_p ;

the other of said interfaces being capable of propagating said signal frequency wave in a gyromagnetic mode of wave propagation with a phase constant β_s ;

said other interface being further capable of propagating a third signal in a gyromagnetic mode of wave propagation;

said third signal having a frequency $(f_p - f_s)$ and a phase constant substantially equal to the difference between β_p and β_s ;

and said interfaces being spaced in distant t given by

$$\frac{2.3}{|\beta|} < t < \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency wave.

3. A parametric amplifier comprising first and second longitudinally spaced rectangular waveguides supportive of wave energy at a signal frequency f_s and at a pumping frequency f_p higher than said signal frequency in a normal waveguide mode of propagation;

a third section of waveguide proportioned to be cut-off at said signal frequency and at said pumping frequency for said normal mode of wave propagation disposed between said first and second waveguides;

means for propagating said wave energy through said third waveguide in a gyromagnetic mode of wave propagation comprising three slabs of magnetically biased gyromagnetic material having different saturation magnetizations;

said slabs forming a composite structure with one of said slabs located between and contiguous with the other two slabs defining a pair of gyromagnetic-to-gyromagnetic interfaces;

one of said interfaces being capable of supporting wave energy in a gyromagnetic mode of wave propagation at said signal frequency f_s and at an idler frequency f_i with phase constants β_s and β_i respectively;

and the other of said interfaces being capable of supporting wave energy in a gyromagnetic mode of wave propagation at said pumping frequency f_p where $f_p = f_s + f_i$ with a phase constant $\beta_s + \beta_i$;

11

said interfaces being separated a distance t given by

$$\frac{2.3}{|\beta|} < t < \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency signal.

4. The combination to claim 3 wherein the saturation magnetization of said one slab is intermediate the saturation magnetization of the other two slabs.

5. A parametric amplifier for amplifying signal frequency wave energy comprising a signal source having a frequency f_s for supplying signal wave energy to said amplifier;

a pumping source having a frequency f_p higher than f_s for supplying pumping energy to said amplifier;

a pair of longitudinally spaced waveguides of rectangular cross section supportive of said signal and said pumping wave energy;

each of said guides having a pair of narrow and a pair of wide conductive walls;

said guides being aligned along a common longitudinal axis with the wide walls of each parallel to the wide walls of the other;

a ferrite-loaded section of wave path proportioned to be cut-off at said signal and said pumping frequencies comprising a third section of conductively bounded waveguide connecting said first guide and said second guide;

three slab-like elements of ferrite material having different saturation magnetizations located within said third section;

each of said elements having a pair of parallel broad surfaces which extend throughout the length of said third section in a direction parallel to the narrow walls of said pair of guides with a broad surface of each element parallel to and contiguous with a broad surface of the next adjacent element thereby defining a pair of ferrite-to-ferrite interfaces;

one of said interfaces being supportive of wave energy in a gyromagnetic mode of wave propagation at the frequency of said signal source and at a second frequency equal to the difference between the pumping frequency and the signal frequency;

the wave energy at said signal frequency and at said second frequency having a propagation constant β_s and β_1 respectively;

the other of said interfaces being supportive of wave energy in a gyromagnetic mode of wave propagation at said pumping frequency and having a phase constant equal to the sum of β_1 and β_s ;

said interface being separated by a distance t given by

$$t \approx \frac{2.3}{|\beta|} \text{ to } \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency wave;

means for coupling wave energy between said pair of guides and said third section comprising a tapered extension of said elements into said said pair of waveguides;

and means for magnetically biasing said elements in a direction parallel to their broad surfaces.

6. A parametric amplifier comprising a two conductor transmission line having an inner conductive member and an outer conductive member surrounding said inner conductive member;

said line being capable of supporting wave energy at a signal frequency f_s in a TEM mode of wave propagation;

said outer conductive member capable of supporting pumping wave energy at a frequency f_p higher than said signal frequency in one of the normal waveguide modes of propagation;

a portion of said line containing a slab of magnetically biased gyromagnetic material capable of sup-

12

porting gyromagnetic modes of wave propagation at said signal frequency and at said pumping frequency with phase constants β_s and β_p respectively;

said material being further capable of supporting wave energy at a third frequency equal to $f_p - f_s$ with a phase constant approximately equal to $\beta_p - \beta_s$;

said material being asymmetrically disposed between said inner member and said outer member;

said outer member having reduced cross-sectional dimensions over said portion of line whereby said outer member is cut-off at said pumping frequency for propagation in said normal waveguide mode;

and means for coupling said signal frequency wave energy from said TEM mode to one of said gyromagnetic modes of wave propagation comprising a plurality of electrical discontinuities longitudinally distributed along said portion of line.

7. The amplifier according to claim 6 wherein all of said gyromagnetic modes propagate along the same boundary of said gyromagnetic material.

8. The amplifier according to claim 6 wherein said gyromagnetic modes propagate along different boundaries of said gyromagnetic material and wherein said boundaries are separated by a distance t given by

$$t \approx \frac{2.3}{|\beta|} \text{ to } \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency wave.

9. A parametric amplifier comprising first and second sections of longitudinally displaced circular waveguides supportive of electromagnetic wave energy in the circular electric mode of wave propagation at a signal frequency f_s and at a pumping frequency f_p higher than said signal frequency;

a length of reduced diameter circular waveguide proportioned to be cut-off for said circular electric mode of wave propagation at said signal and at said pumping frequency located between said sections of waveguide;

and means for propagating said wave energy through said length of cut-off waveguide comprising three hollow coaxial circular cylinders of circumferentially magnetically biased gyromagnetic material having different saturation magnetization;

said cylinders extending coaxially along said length from said first waveguide to said second waveguide with a surface of each of said cylinders contiguous to at least one surface of another of said cylinders to define a pair of gyromagnetic-to-gyromagnetic boundaries;

one of said boundaries being supportive of wave energy in the gyromagnetic mode of wave propagation at said signal frequency with a phase constant β_s and at an idler signal at a frequency $f_p - f_s$ with a phase constant β_1 ;

the other of said boundaries being supportive of wave energy in a gyromagnetic mode of wave propagation at the pumping frequency with a phase constant substantially equal to $\beta_s + \beta_1$;

and said boundaries being spaced from each other a distance

$$t \approx \frac{2.3}{|\beta|} \text{ to } \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency wave.

10. A parametric oscillator comprising a magnetically biased gyromagnetic material capable of propagating wave energy along its boundaries in the gyromagnetic modes of wave propagation at a pumping frequency f_p with a phase constant β_p and at two other frequencies f_1 and f_2 with phase constants β_1 and β_2 respectively where $f_1 + f_2 = f_p$ and $\beta_1 + \beta_2 = \beta_p$;

means for applying pumping wave energy to said os-

13

cillator at a level greater than the threshold level for said oscillator;

means for inducing said gyromagnetic propagating modes in said material at said pumping frequency; and means for extracting energy from said oscillator at at least one of said lower frequencies.

11. The oscillator according to claim 10 wherein said modes propagate along different boundaries and wherein the distance t between boundaries is given by

$$t \approx \frac{2.3}{|\beta|} \text{ to } \frac{3.4}{|\beta|}$$

where β is the phase constant of the lowest frequency wave.

14

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